X-RAY AND GAMMA RAY SPECTROMETER FOR THE HEAT FLOW AND PHYSICAL PROPERTIES INSTRUMENT (HP^3) ON THE *EXOMARS* GEOPHYSICAL AND ENVIRONMENTAL PACKAGE

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ABSTRACT

In this study we highlight the enhancement of one of the proposed core experiments on the Mars Long-Lived Surface Package (ML2SP) proposal to the European Space Agency for the *ExoMars* Geophysical and Environmental Package (GEP). The instrument is the Heat Flow and Physical Properties Package (HP^3), led by Tilman Spohn at DLR Berlin (formerly at Institut für Planetologie, Münster). HP^3 is a sub-surface suite of sensors aimed at measuring planetary surface heat flow, an important geophysical parameter never before measured on Mars. The experiment comprises a suite of three sensor subsystems deployed from a surface station to a depth of several metres by means of a tethered mole. Mechanical properties are derived from measurements of the dynamics of mole penetration; thermal properties are measured using sensors distributed along the umbilical tether, and the bulk density profile is measured using a gamma-ray backscatter densitometer housed within a payload compartment at the lower end of the tether. The densitometer comprises a radioisotope source (^{137}Cs), high density shielding, two semiconductor gamma ray detectors and associated front-end electronics. The Open University and University of Leicester teams have been working on the development of a Monte Carlo model for the probe as well as the laboratory breadboard model. In this study we describe the laboratory programme and show some of the results obtained. The enhancement requires the inclusion of both X-ray and Gamma Ray spectrometers in the instrumented mole, which will provide details of the elemental composition of the Martian surface as a function of depth. The enhancement will also provide details of natural sources of radiation such as U, Th and K. The compositional information will allow for a more accurate estimate of the specific heat capacity of the material surrounding the mole, thus providing more accurate heat flow measurements.

1. INTRODUCTION

The Martian sub-surface preserves records of geological and climatic evolution and plays host to water ice, possibly habitable environments and perhaps, traces of life. The development and flight of a mole-deployed X-ray / γ-ray instrument for the *ExoMars* Geophysics and Environmental Package (GEP) will enable the geophysical and geochemical profiling of the first 5 m to 10 m of the sub-surface at the targeted landing site. Previous Martian missions, e.g. Viking Lander, have profiled no deeper than 30 cm and the results from Spirit and Opportunity indicate a small-scale compositional heterogeneity [1]. The X-Gamma experiment may be *ExoMars*' only opportunity to make geochemical measurements below the oxidant extinction depth, which has a global mean of 2 m to 5 m by some models [2], greater than the depth accessible by the *ExoMars* drill. A mole deployment system is already base-lined for the GEP.

2. SCIENCE OBJECTIVES

The proposed X-Gamma instrument has three simultaneous measurement modes (A) ~200 to 700 keV; (B) 1 keV to 20 keV; (C) 30 keV to at least 2.5 MeV; however, this limit could be increased above 6 MeV if a large volume detector is selected to measure gamma rays produced via neutron activation processes.

The instrument will perform a number of measurements on the structure and elemental compositions of the Martian sub-surface. Bulk density will be measured using mode (A); elemental composition will be measured using modes (B, C). The instrument will determine the relative abundances of major rock-forming elements, modes (B, C); the abundance vs. depth of meteoritic nickel, modes (B, C); the presence of water/ice, from prompt neutron activation products, mode (C) [3]; the abundances of carbon and nitrogen, mode (C), phosphorus and sulphur, modes (B, C); radioactivity levels generated by particle-induced reactions, mode (C), and the concentration of natural radioisotopes (K, U, Th), mode (C). Detailed lists of elements detectable by complementary X-ray and neutron activation techniques more are given by Nair et al., 2004 [4] and Meyer (ed), et al. [5], 1995.

The neutron flux on the Martian surface has been reported to be higher than expected [6]. The estimated fluence at the surface of 1 MeV neutrons is of the order of 2×10^7 neutrons cm^{-2} MeV^{-1} for the duration of a 1956 equivalent solar particle event. At thermal neutron energies the fluence levels are an order of magnitude higher. The continuous exposure of the surface to neutrons and the pulsed nature of the exposure due to solar events implies that both prompt and delayed activation products should be detectable.

To assess the habitability of the Martian sub-surface, the instrument will also carry out measurements of elements that are required as nutrients (C, N, P and S) and elements such as iron that might serve as energy supplies for organisms that use inorganic compounds for energy (chemolithotrophic organisms). Determining the relative abundances of these elements in the sub-surface is essential for a comprehensive understanding of habitability and how the potential habitability varies with depth.

The bulk density profile constrains the geological interpretation of the local deposits, e.g. fluvial and aeolian activity, volcanism, glaciation and erosion, the depth of loose deposits and bedrock, petrology and possibly sedimentary layering. Constraints on porosity, and thus permeability, are important for assessing the capacity of the sub-surface material for harbouring and transporting volatiles / liquids, atmospheric constituents and perhaps life. Through microstructural modelling and mechanical measurements from the mole, the bulk density constrains a host of other physical and geotechnical parameters. Together with thermal measurements, a ‘ground truth’ thermal inertia can be determined, both at the surface accessible by orbital measurements, but more importantly at depths greater than those accessible from orbit. Surface heat flow is currently known only for the Earth and rather poorly for the Moon [7, 8].

The principle for heat flow measurements is described in detail by [9, 10] and the thermal conductivity of the regolith, λ, can be calculated via the following expression:

$$\lambda = \kappa \rho c, \tag{1}$$

where κ is the thermal diffusivity of the regolith, ρ is the bulk density of the regolith and c the heat capacity.

The bulk density profile is important in order to measure the surface heat flow on Mars. The error in heat flow measurements can be reduced by the composition measurement capability of the X-Gamma instrument. This profile will provide an improved measure of the heat capacity of the crust as a function of depth given that the heat capacity is element dependent [10]. Martian thermal evolution models will also be supported by X-Gamma’s measurements of the natural radioisotopes.

Once deployed to the maximum possible depth by the mole, the instrument will continue to operate. This allows not only the elemental composition of the surrounding material to be measured very accurately, but also any changes to be monitored. These may arise from the seasonal exchange of atmospheric constituents and volatiles with the sub-surface, an important aspect of Martian astrobiology and meteorology. Fig. 1 shows an example of an X-ray spectrum that would be within the ranges to be used by X-Gamma, indicating the rich array of geochemical information obtainable at every measurement point (every few cm) examined by the instrument on its sub-surface journey. In addition the gamma ray mode will allow detailed evaluation of radioactive nuclei and neutron activation products.

3. THE X-GAMMA INSTRUMENT

3.1. The HP^3 Probe

The current incarnation of the HP^3 instrument is shown in detail in Fig. 2 and 3. In the schematic diagram (Fig. 2) the dimensions of the basic structure are visible in addition to the radioactive source and shielding. The CdTe detectors, supplied by Amptek Inc., USA, are 5 x 5 x 0.75 mm^3 (18.75 mm^3) in size and as shown in Fig. 2 there are 2 detectors for the bulk density measurements.

In Fig. 3 we see the engineering drawing of the final configuration of the breadboard model to be delivered to the European Space Agency later this year.

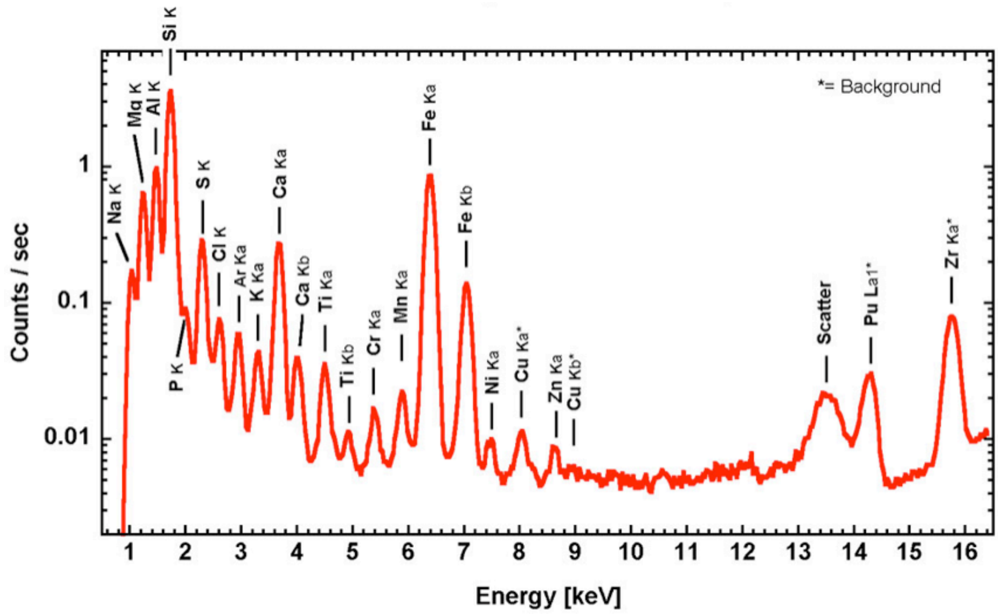

Fig. 1. MER APXS spectrum from Mars [1]. Prominent lines are labelled. Spectral artefacts from the instrument and characteristic elemental lines from the sample are present.

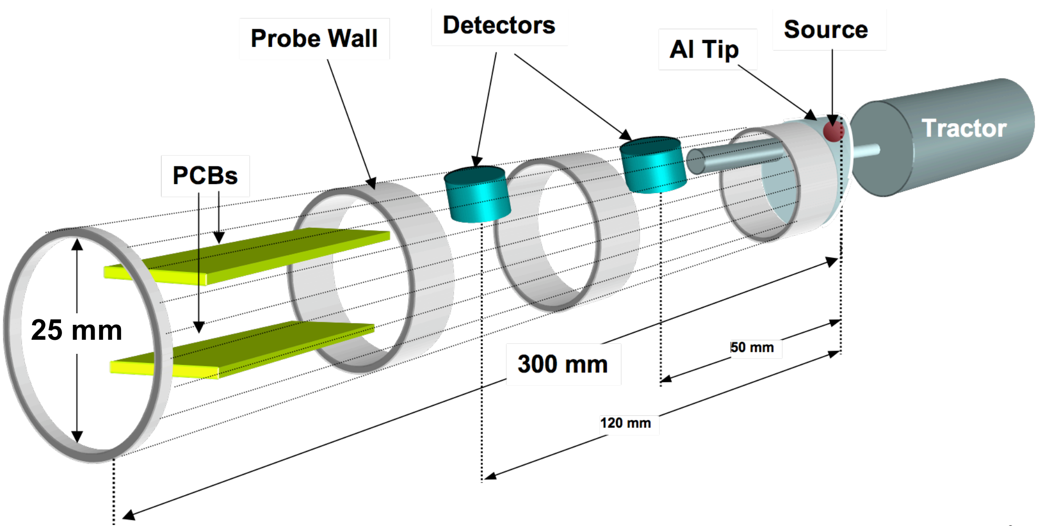

Fig. 2. Schematic diagram of an early configuration of the densitometer and tractor component of the HP^3 mole. This configuration was used in the development of early Monte Carlo models of the mole. Two 18 mm^3 CdTe detectors are visible along with the ^{137}Cs source and tungsten shield.

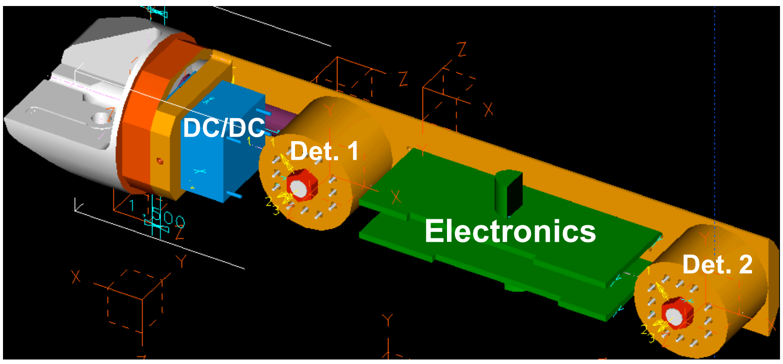

Fig. 3. CAD image of the breadboard configuration for delivery to ESA in 2006, showing (L to R) the tip of the payload compartment housing the source, shielding and DC/DC converter, the first detector, the preamplifier and bias filter boards, and the second detector. The flight model instrument would employ ASICs instead of the boards shown.

The probe tether will be used to facilitate the measurement of the heat flow on the planetary surface. The instrument makes use of the line heat source (LHS) method [9, 11, 12] or the self-heating effect of an internally heated long sensor, which is surrounded by the sample material. The LHS technique is a transient method and records the temperature rise within the sensor as a function of time and heating power per unit length. For the LHS method to work, the length of the sensor has to be greater than 30 times the magnitude of the radius of the sensor [9]. The LHS method works on the assumption that the surrounding medium can be approximated by an isotopic and homogeneous medium in both azimuthal and axial directions.

This tether is a 5 m long multilayer flexible copper and Kapton cable based on cables developed by Oxford University for use on Cassini, Meteosat Second Generation and at CERN. The cable is challenging largely because of the use of high spatial resolution copper tracks over a large area. This experiment consists of resistance thermometers and heaters distributed along the cable and implemented as high resolution etched patterns in the copper tracks. A complete prototype cable including sensors has already been manufactured.

Calibration of the densitometer was carried out at the Open University; this was done by inserting the prototype probe, incorporating the two detectors and the source, in cylindrical standards of varying density. The calibrations standards varied in density from 1 g cm^{-3} to 10 g cm^{-3}. Calibration spectra were recorded (See Fig. 4) and the ratio of the counts in each of the detectors calculated as a function of density. For the bulk density measurements we used the count rate of the continuum in a broad energy window, 250-500 keV, dominated by Compton scattering of the ^{137}Cs source's 662 keV photons in the surrounding material. In Fig. 4 we can see that as the bulk density increases, more photons are scattered into the detectors. This bulk density measurement technique was used in the 1960s and 1970s by the Soviet Union for surface density instruments for use on the Moon, Mars and Venus [13]. This technique is commonly used for terrestrial applications including well logging by the oil and gas industry, albeit with much larger and more massive instruments.

3.2. The Monte Carlo Model

A Monte Carlo model of the current version of the densitometer for HP^3 was developed using MCNPX^{TM}. The schematic diagram, Fig. 1, best describes the structure incorporated in the model. The model was used to generate a calibration curve for the densitometer. The calibration curve of count rate in the detectors versus density was compared to the data recorded with the breadboard model. And the results are shown in Fig. 5.

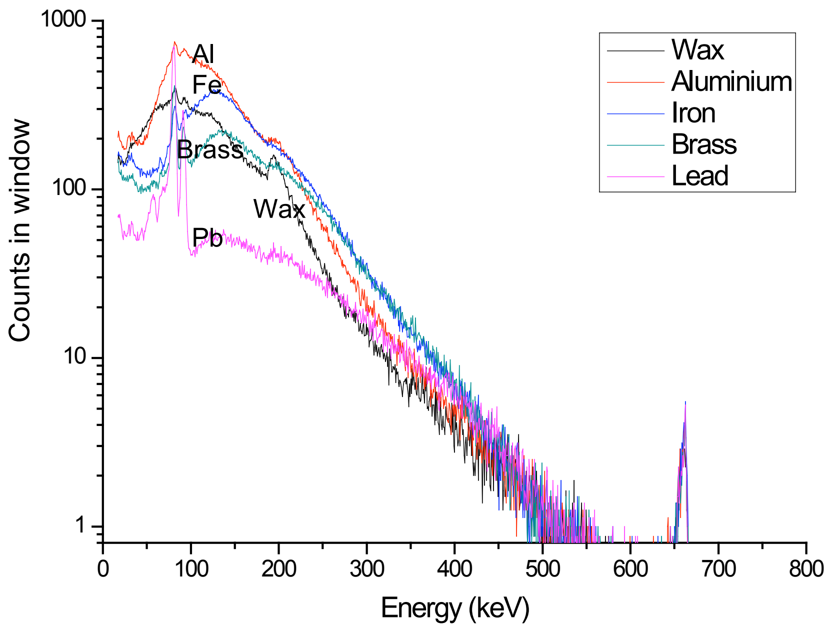

Fig. 4. Spectra obtained using the lab densitometer shown in Fig. 3. The count rate in the range 250-500 keV depends almost entirely on the bulk density of the material, due to the dominance of Compton scattering and the fact that for most elements (except H), A/Z~2. A peak from the 662 keV Cs source and lead fluorescence X-rays are also visible.

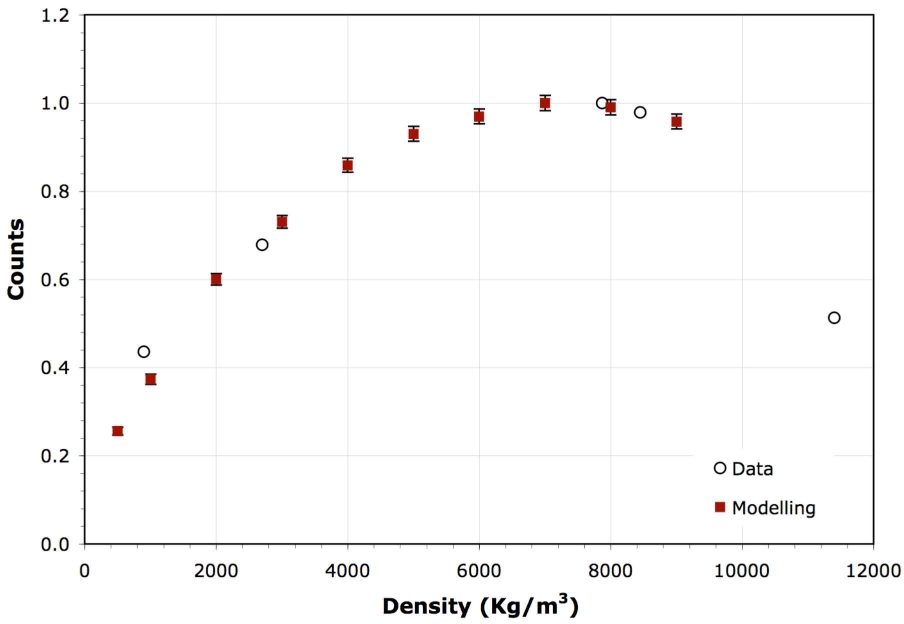

Fig. 5. Calibration graph, showing normalised count rate vs. bulk density. Good agreement is seen between the laboratory data and Monte Carlo model.

3.3. The Hybrid Detector Concept

The enhancements to the second generation HP^3 probe comprise larger volume gamma ray CdTe detectors, one of which will be combined with an X-ray Si detector.

CdTe is known for its high resolution 1% at 662 keV [14] and although a pulse shape processor is required to reduce any charge redistribution [15] there are no stringent cooling requirements with nominal operation at -20 ^{o}C to -30 ^{o}C.

A larger volume will expand the detectable gamma ray energy range beyond the current limit of 1 MeV. Recent experiments at the University of Leicester with a 500 mm^3 CdTe detector, supplied by EURORAD, indicated that we could increase the detection efficiency of our probe sensors to 2.5 MeV. Our aim is to go beyond 10 MeV.

In order to determine the feasibility of achieving some detection efficiency at such high gamma ray energies, we are developing a Monte Carlo model to test the efficiency of CdTe as a function of volume. In the model, a spherical CdTe detector was exposed to a number of discrete gamma ray energies ranging from ^{137}Cs 662 keV gamma rays to prompt activation products from nitrogen above 10 MeV. The initial results are shown in Fig. 6. The energy cut off for the current detectors used in the breadboard HP^3 is around 1 MeV; detection efficiency drops off rapidly at high energies. Increasing the volume to 500 mm^3 and possibly 2000 mm^3 (using 4 x 500 mm^3 units) the efficiency of the detector can be increased to energies above 10 MeV; however a more detailed model needs to be developed coupled with an experimental campaign, which begins later this year. In Fig. 6 we see some of the typical gamma ray energies one would hope to detect with the system.

The densitometer design shown in Fig. 2 could be modified to resemble what is shown in Fig. 7. Placing a large volume detector at the base of the mole and the ^{137}Cs source at the top of the mole should make better use of the mole volume (especially the hollow tip) and possibly allow a reduction in the overall length of the mole to less than 250 mm.

The enhanced X-Gamma system has an additional X-ray detector to facilitate X-ray fluorescence measurements of the regolith as a function of depth. The schematic diagram (Fig. 7) shows the X-ray source, which will stimulate the production of fluorescence X-rays that will greatly constrain the composition of the regolith. The X-ray source should stimulate X-ray emissions ranging in energy from 1 keV to 30 keV in order to detect a broad range of elements. Sources could include ^{55}Fe (5.898 keV), ^{109}Cd (88 keV), ^{241}Am (59 keV, 33 keV, 26 keV) or combinations of two sources. The X-ray transmission windows will be of a suitable material that will maximise the X-ray transmission efficiency at energies above 1 keV, without compromising the integrity of the probe. Materials such as Kapton, Uralene, Teflon, Mylar and polypropylene will be considered for the X-ray window; combinations of materials may be required to best protect the detector.

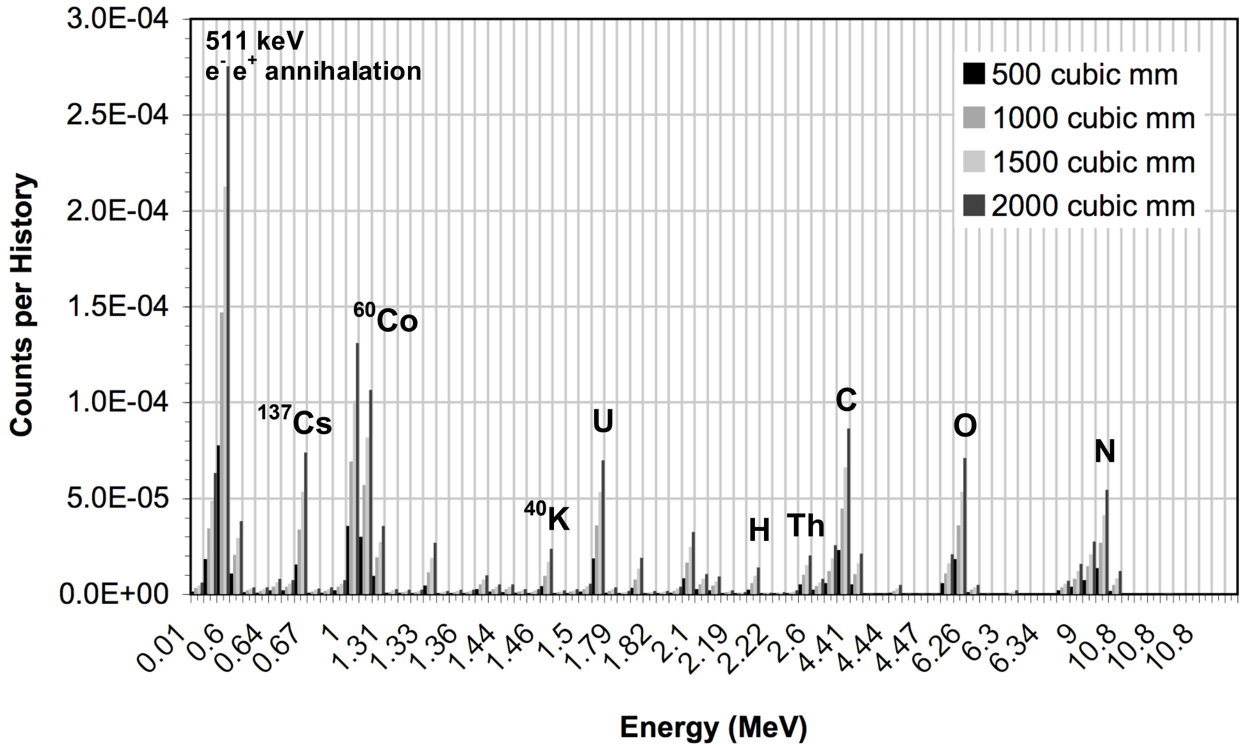

Fig. 6. Preliminary results from the computational model of detection efficiency versus detector volume as a function of energy. Typical gamma ray lines were included in the model to determine the relative increase in detection efficiency as a function of detector volume. The counts were normalised per photon history and the total number of histories was of the order of 4 x10^8 directed at the detector for the various simulations. The energy cut off for the current 18 mm^3 detectors incorporated in the densitometer, part of HP^3, is at 1 MeV.

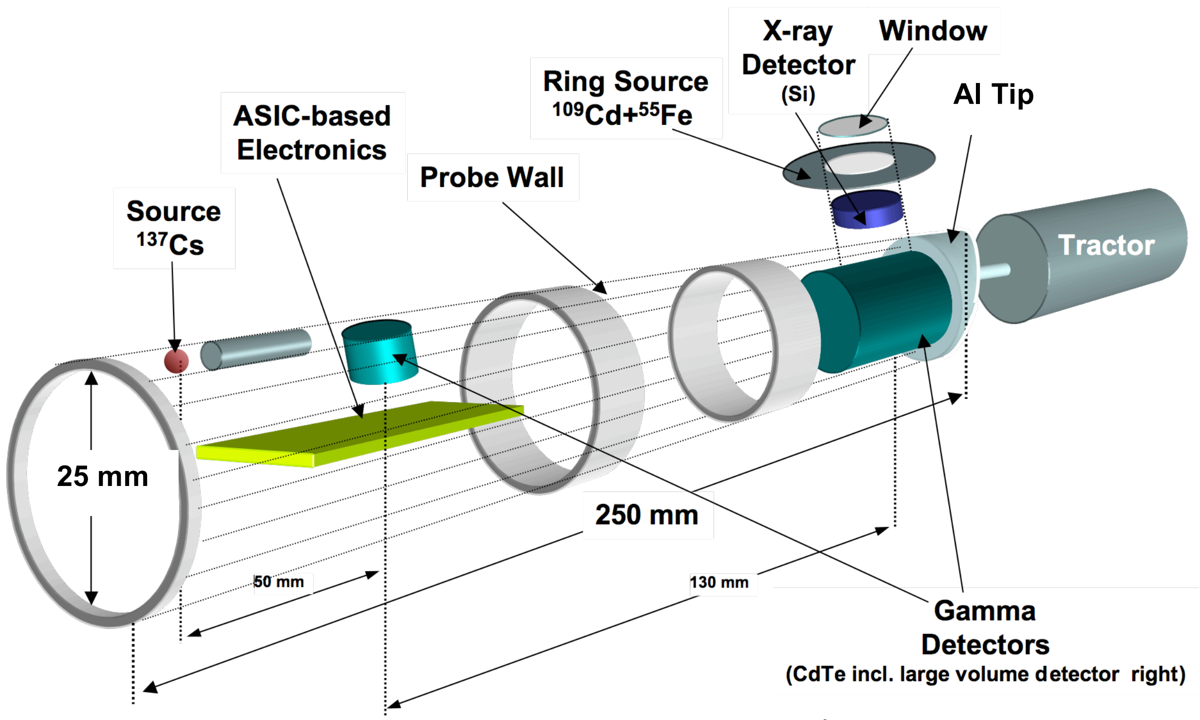

Fig. 7. Schematic diagram of the modified densitometer and tractor component of the HP^3 mole. This is a possible configuration for X-Gamma, with the large volume detector > 500 mm^3 at the base of the mole, hybridised with an X-ray spectrometer. The second gamma ray sensor ~500 mm^3 in size would be at the top of the mole close to the tungsten shield and ^{137}Cs source.

Elemental composition is measured by peak detection in the X-ray fluorescence and gamma spectra, while the bulk density is measured by using the technique described in Section 3.1.

4. CONCLUSION

In this paper we have outlined the current baseline breadboard design for a penetrometer aimed at measuring heat flow through a planetary regolith as a function of penetration depth. The instrument incorporates a densitometer for bulk density measurements using the well established gamma ray backscatter technique. We have proposed an enhancement to the probe in the form of a hybrid X-ray gamma ray detector consisting of a CdTe gamma ray spectrometer and a silicon-based X-ray sensor. This enhancement will enable a broad spectral analysis of the composition of the planetary surface as a function of depth. In addition we have proposed the inclusion of large volume gamma ray sensors in order to broaden the detection efficiency of one of the gamma ray sensors in order to detect gamma rays from the neutron activation of lighter elements such as carbon, oxygen and nitrogen.

A Monte Carlo model was developed to generate a calibration curve for the densitometer, part of HP3, and the results show good agreement with experimental data. In addition a Monte Carlo model is being developed for the case of the large volume detector. Preliminary results indicate that detector efficiency may exceed the required 10 MeV in order to detect gamma rays from light elements (C, O, N) activated by neutrons; however, experimental validation is required.

5. REFERENCES

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